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OPERATION OF THE 25 kW NASA LEWIS RESEARCH CENTER SOLAR REGENERATIVE FUEL CELL TESTBED FACILITY

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ABSTRACT

Assembly of the NASA Lewis Research Center (LeRC) Solar Regenerative Fuel Cell (RFC) Testbed Facility has been completed and system testing has proceeded. This facility includes the integration of two 25 kW photovoltaic solar cell arrays, a 25 kW proton exchange membrane (PEM) electrolysis unit, four 5 kW PEM fuel cells, high pressure hydrogen and oxygen storage vessels, high purity water storage containers, and computer monitoring, control and data acquisition. The **fuel cell and electrolyzer subsystems' installation was carried out by the Jet Propulsion Laboratory** (JPL). The photovoltaic arrays and electrical interconnect to the electrolyzer were provided by the U. S. Navy/China Lake Naval Air Warfare Center. JPL is responsible for conducting the testing and operations at the LeRC facility.

There are multiple objectives for this program. The near term objectives are: (1) design, assemble, and test the solar RFC power plant system to serve as a pre-prototype operational testbed facility; (2) evaluate performance criteria of the total system, subsystems, and components against various operational duty cycles; and (3) develop automation and controls commensurate with advanced system operating requirements. The long term objectives are: (1) develop a highly reliable, long life, highly efficient solar RFC power system for future manned space missions; and 2) demonstrate the dual use aspects of RFCS applicable to commercial and military applications. The system description and initiation of system testing constitute Phase I of multiple activities planned to take place in the next few years. System modeling is being performed in parallel with the experimental testing and will be used to determine the most efficient system design, from the standpoint of weight, volume and cost of electrical power.

INTRODUCTION

The National Aeronautics and Space Administration (NASA) has continued to pursue the exploration of space via both robotic and human missions. As human exploration tasks grow in length of time in space, a variety of problems are encountered, one of which is the provision of power for operating the human habitat. Small nuclear-based power generators have been shown to provide long term sustainable power on satellites sent on exploration missions to the outer reaches of our Solar System and beyond. However, the usc of large nuclear power plants, necessary for providing kilowatts of power for life support systems, has not been completely agreed upon for future human missions for a variety of reasons, including the concerns about how safely they may be integrated into the life habitat operations. Unlike MIR and the future Space Station, a Lunar operation would require considerably more power over a vastly different operating duty cycle, suggesting the need for a reliable electric power plant that can be closely integrated into all functions of the habitat, including the heat produced from the electrical power generation or consumption. A Solar Regenerative Fuel Cell (RFC) system provides this possibility, and coincidentally furnishes a backup supply of oxygen and water available to the inhabitants in the event of emergencies or unforeseen problems.

The design of a Lunar habitat solar RFC power plant is made up of a combination of subsystems: photovoltaic (PV) panels **for solar-to-electric** power generation during the cyclic daylight period, approximately fourteen earth days; an electrolysis unit that uses DC electricity from PV to electrochemically convert water into hydrogen and oxygen and low grade heat; fuel cells that electrochemically convert hydrogen and oxygen into DC electricity, water and low grade heat during the cyclic night period, approximately fourteen earth days; storage tanks for pure water and high pressure hydrogen and oxygen; and automated controls. One approach for operating such a system would require the PV to supply both the habitat electrical and thermal energy needs during sunlight hours, as well as electrical needs for generating adequate hydrogen and oxygen to be used by fuel cells during hours of darkness. For this type of system, two candidate technologies have the greatest potential for adaptation to a

Lunar environment; one utilizes an alkaline (potassium hydroxide, KOH) electrolyte, **the other utilizes a proton** exchange polymer membrane (PEM) as substrate for electrolyte.

From the results of a preliminary system study of a 25 kW electric power generator for a Lunar habitat (Huff, 1991), in which alkaline technology was compared to a PEM technology for use in both electrolysis and fuel cell units, significant advantages associated with adopting PEM technology were identified. A goal for a complete cycle system efficiency, excluding the PV, was 65%, i.e., - 659" efficiency in both electrolysis and fuel cell conversions. The primary reasons that make PEM more attractive than KOH are (a) PEM fuel cells and electrolysis units require less pressure control complexity, and (b) containment of the aqueous KOH electrolyte is much more difficult than a polymeric membrane, i.e., Nafion™. Other issues that make PEM more attractive deal with maintenance: the polymer does not have to be safeguarded **against carbon dioxide, in the event that air from the habitat** would be used for fuel cell cathode feed; assembly and disassembly of a PEM unit does not require special handling precautions against caustic KOH, nor is there significant concern about the dilution or contamination of the electrolyte when exposed to normal atmospheric conditions. Other fuel cell operating properties, including low temperature (< 80" C), current density (- 300 ma/cm^2), cell voltage (-0.75 v), and pressure (-304 kPa), for example, were very similar between the PEM and KOH. It was pointed out that the mass of hydrogen and oxygen required for the prescribed 672 hour cycle, consumed during the 369 hours of operation through the night and produced during the 303 hours of day, was nearly equivalent to the combined mass of the fuel cells, electrolysis unit, and the outlined supporting equipment.

A subsequent investigation was conducted to determine the mass requirement associated with establishing a regenerative PEM fuel cell power plant on the surface of the Moon (Jan, 1993). The hypothetical system used for this study was based on a conceptual design that was also 25 kW in size, but assumed 288 hours of electrolysis operation, i.e., hydrogen and oxygen production, and 384 hours of fuel cell operation on the stored hydrogen and oxygen over the same nominal 692 hour cycle. The design focused on a system that would require a minimum of human intervention, which had been identified in previous studies to be a major contributor to recurring supplies. By reducing the amount of system maintenance, a corresponding reduction in life support systems supplies would be required, which result.. in a reduction in supply mass. A number of issues were specifically examined to determine the most viable system for this application. The main issues were: (1) cryogenic versus pressurized storage of hydrogen and oxygen; (2) details defining support equipment requirements; and (3) the impact of human intervention in meeting maintenance requirements.

While a majority of the items on both lists of components are common and contribute nearly the same mass, i.e., electrolysis unit, hydrogen and oxygen quantities, fuel cells, heat exchangers, and PV, additional mass is required to operate a cryogenic system versus a high pressure storage system. When the electrolysis unit is operated at 20.7 Mpa of pressure, only the water fed to the unit must be pumped and the hydrogen and oxygen produced are delivered to the storage system at storage pressure, i.e., no additional gas pumping is required. Since little technical information is available concerning the actual operating equipment and conditions associated with cryogenic, rotating-shaft equipment operating with two-phase systems (gas/liquid) in microgravity, assumptions based on 1 G were conservatively used. While the savings determined in that study constitute only about 7% of the original mass of equipment (-9300 kg) that would be installed for a Lunar operation, the projected mass calculated to be necessary in sustenance required for the human support potentially required for maintenance of the cryogenic equipment is on the order of 20% of tbc initial installed mass each year. (T'he basis for this calculation was the model developed for life support systems. Little information is available dealing with actual operating equipment, the associated maintenance requirements, and additional human support needs for such a system in a microgravity environment. There were, however, two very important conclusions from this study: (1) the RFC system needs to bc as simple and dependable as possible for both initial and maintenance mass reductions; and (2) the operation of a system that could serve as a basis for determining actual technology status and development is necessary.

In response to these conclusions, NASA LeRC and JPL embarked upon an effort to design, assemble and operate a testbed facility to evaluate the technology associated with such a solar regenerative power plant system. Although the effort was initially aimed at a future NASA application, the potential for use in numerous terrestrial applications, both commercial and military, were also identified, where isolated, dependable, low-maintenance electrical power is required. The operation was, therefore, targeted for dual purposes and the importance of understanding the system integration, and the unique operation and control complexity associated with both applications, placed added value on these goals. The usc of off-the-shelf equipment serves to illustrate the technical status associated with a RFC system design, integration, and control, at this time, while still addressing the distinction in specific requirements peculiar to each type of application.

FACILITY DESCRIPTION

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The testbed facility assembled for this project is located in a dedicated building on three acres of land at Edwards Air Force Base in Edwards, California. This site, located in the high desert of California, was chosen because of its consistent annual supply of sunlight, availability of adequate space and facilities, secure but unrestricted access, dedicated facilities, and low maintenance. The building incorporates integral safety features and houses the fuel cell, electrolysis, water storage, and controls. The immediate surroundings accommodate the high pressure hydrogen and oxygen storage and thermal management, and a field of PV arrays stretches over a two acre area on the southern side of the building.

This facility is designed to serve as a testbed, capable of incorporating a variety of fuel cell and electrolyzer types and configurations, along with all ancillary equipment. Currently, two separate test stands for fuel cell stacks are co-located for operation from common hydrogen, oxygen, nitrogen and thermal management sources. The electrolysis unit is configured to be able to operate from either the grid (AC), that will permit testing and operation at any time, or from a 50 kW (present) PV array (DC) for stand-alone operation. Pressure vessels for hydrogen storage at pressures up to 20.7 MPa and oxygen storage at pressures up [o 17.3 MPa. serve as either sources of reactants to the fuel cell test stands or as recipients of delivered gas from the electrolysis unit. Figure 1 illustrates a schematic of the subsystems integrated into the solar RFC testbed facility.

Specific Considerations

Fuel Cells.

The current configuration of one test stand for fuel cells incorporates four, 5 kW, PEM stacks, manufactured by Ballard Power Systems, Inc. (Vancouver, B .C.) and provided to this project by the Canadian Department of Defence. These are Mark 5 model stacks which have been constructed to enable operation at high pressures ($\leq$ 1 MPa), have 48 cells, each with an active cell area of 232 cm^2. The four stacks are manifolded in parallel connections to common hydrogen, oxygen, nitrogen, and coolant supplies and to independent electrical leads. The assembly allows for independent operation of each of the fuel cell stacks, both to electric load and to the supply manifolds, to allow for flexibility in operations. Figure 2 shows this configuration.

Operation of these fuel cell stacks is unique in order to accommodate the specific closed loop requirements for NASA, and simultaneously meet the needs of other applications requiring a dedicated source of hydrogen and oxygen, while capturing the product water. Hydrogen delivery is provided to each fuel cell stack, and is allowed to recirculate passively through each stack during operation via an ejector located at the inlet of the delivery manifold. The cathode feed is a specifically determined mixture of oxygen and nitrogen that also recirculates through the fuel cell stacks. The recirculation method employed, however, is an active one, provided by a liquid ring pump that, in the current configuration, operates only at a constant speed. The pump serves two purposes: it recirculates the oxygen-containing gas through the cathode cavities. and it removes the product water. A water separator tower, integral to the recirculated cathode feed, removes the product water from the gas stream. These fuel cells are capable of operating with oxygen concentrations from 21% to 50% (volume), and is referred to as a 'Nitrox' operation by Ballard Power Systems, Inc. This unique feature allows an opportunity to study a fuel cell performance that (1) is closed for dedicated product water recovery, (2) can simulate air performance that is applicable to terrestrial operations or integral with a closed life support system, and (3) can operate at high oxygen content to improve the cathode operation efficiency without necessitating a dedicated pure oxygen operation.

Each fuel cell stack is separately instrumented to measure individual cell voltages within each stack, total stack amperage, pressures, and coolant temperature. Total hydrogen and oxygen flow into the manifold, coolant water conductivity and flow, and system pressures arc also constantly monitored. Hydrogen and oxygen delivery rates are controlled by the electrical demand and the delivery pressures arc preset for a given system operation. In the current configuration, the pressure containment vessel is pressurized with nitrogen during operation, but this is not a required feature for this type of operation.

Electrolysis Unit

The electrolyzer employed in this current operation is a Hamilton Standard PEM unit that was built for, and is owned by, the U.S. Navy for submarine service. It has 83 cells, each with 214 cm^2 active area and capable of operating up to 21 MPa. The system has been modified for this operation to be able to deliver hydrogen at up to -21 MPa and oxygen up to -19 MPa. Control of water delivery, recirculation, and all operational safety features (pressures, pressure differentials, temperature, current) are maintained by an Allen Bradley programmable system. This electrolyzer has been altered to operate with a grid supply or a dedicated supply from the PV array, and will operate to any set delivery storage pressure from 2.1 to 21 MPa. It operates at 230 volts and at amperages from 300 to 1000 ma/cm^2. The power tracker interface unit between the electrolyzer and the PV array was provided by the Naval Air Warfare Center. This unit is designed to transmit power from the two separate PV arrays and provide DC power to the electrolyzer upon demand. Integration of controls between the Labview, Allen Bradley and the electrolyzer allows the unit to be operated manually from Labview at the remote computer terminal in the facility.

Photovoltaic Array

The photovohaic array, provided by the Naval Air Warefare Center, is comprised of two separately operating arrays manufactured by two different manufacturers. They both are manufactured of thin film CdTe material and installed to serve two purposes: (1) to investigate the performance of this technology relative to the well-tested silicon photovoltaic equipment; and (2) to provide power to the electrolyzer. The two arrays are installed within 100 feet of each other near the testbed facility. Inside the facility building, both arrays are connected to a unit originally intended to serve as a maximum power tracker that would provide current at the maximum power level of each array. However, it was modified to be able to deliver prescribed currents (above the threshold of 90 amps for the electrolyzer to startup) at 250 VDC, and permit either singular or dual operation in supplying the current demand as required and as entered at the remote terminal.

TEST OPERATIONS

At the current time, testing in the fuel cell testbed facility is delegated to either fuel cell stack operation or electrolysis operation, not both simultaneously. Operation of both is monitored from separate computers both utilizing Labview software. Placing electrical loads on the fuel cell stacks is currently done manually, but future operations will incorporate computer controlled electrical loading as well. Changing the storage pressures and current of the electrolyzer are done from the computer. All data are displayed on the screen and also saved for subsequent inquiry and/or plotting. Typical performance curves of the electrolyzer arc provided in Figures 3 and 4, showing nearly constant generation rate of both hydrogen and oxygen over an increase of delivery pressure from 5.5 to 8.7 MPa at a constant current density of 800 ma/cm^2 (Figure 3), and a steady increase in hydrogen and oxygen production rate at a constant delivery pressure of 8.7 MPa as a function of an increase in current density from 500 to 800 ma/cm^2 (Figure 4).

The PEM fuel cell stacks have been operated over the entire range of output, from 1 kW to 5 kW each, a total operation of 4 to 20 kW. The system, i.e., fuel cells, water separator, coolant loop, cathode recirculation loop, and water recovery, all functioned as designed. The normal operating conditions are at a 50% oxygen concentration in the Nitrox, constant flow cathode recirculation loop, constant coolant (water) flow with variable external coolant flow, ejector recirculation on the anode, and controlled variation on the electrical load. Normal operating temperature and pressure are 353 K and 275 kPa.

Utilization of the PV array for operation of the electrolyzer has been demonstrated over a range of varying conditions. in order to demonstrate the capability of the PV to provide the necessary cur-rent for startup and continued operation of the electrolyzer, input from pilot photovoltaic cells are incorporated into the Labview control of the electrolyzer. When the solar radiation is adequate to provide adequate current density to sustain startup conditions for the electrolyzer, i.e., 85 amps at 230 v, the signal to begin electrolysis operation is given to the controller and operation can be initiated and sustained. In Figure 5 is an illustration of various operating conditions for the electrolyzer utilizing PV power. At the time when the PV arrays could sustain current density adequate for startup and operation of the electrolyzer, preset at the computer for demand on the "Maximum" power trackers, the electrolysis started, i.e., approximately 8:15 AM, point A. According to the input settings, both arrays contributed nearly the same amperage, - 45 amps, for a total of 90 amps for startup. Subsequently, various manual alterations in the amount of current demanded from each of the arrays were exercised to demonstrate the system operation, At point B the demand by the electrolyzer was held constant, but current settings from both arrays were equally reduced to a level of 30 amps for a total of 60 amps to the electrolyzer. Each was then incrementally increased in equal amounts to a total of approximately 115 amps. At point C Array #2 was manually shut off and the electrolyzer operation was maintained at a preset maximum delivery of 70 amps by Array #1. When Array #2 was again turned on at a setting of 60 amps delivery, it responded at 60 amps to provide a total of 130 amps to the electrolyzer. Additional changes to the amperage delivery levels of the separate arrays were input at the computer terminal. Point D illustrates first an increase in amperage setting for Array #2, followed by a decrease in both arrays, and subsequently an increase in Array #2 amperage while Array #1 remained at the lower level. This in essence illustrates the ability to switch proportional electrical load on the arrays while under constant electrolyzer demand. At point E, two steps were exercised, the first to turn Array #2 off, the second to turn Array #2 on and Array #1 off, in essence transferring the total load from one array to the other. Point F illustrates a constant operation of 150 amps demand by the electrolyzer that was supplied by a preset 65/35 split between [he array loads, a condition which may be necessary when providing maintenance during operation and which illustrates operation when a performance imbalance between panels of arrays may arise. Point G demonstrates the maximum output from Array #1 with Array #2 at a minimum power mode, and at - 12:30, the unit was manually shut down.

From this test example, it is apparent that a number of operational conditions will need to be examined to develop a data base for planning control strategies and developing hardware. Further tests and operational scenarios will be pursued to explore the system operation and integration factors. Operations that include multiple shut down/start up sequences to evaluate all systems aspects for automated control and back up power requirements will also need to be examined.

OPERATIONAL PROTOCOL

Electrolyzer

Although the environment for operating a RFC at a Lunar outpost is very demanding in many ways, there are some aspects that are simpler than a terrestrial operation. A NASA application will require storage of both hydrogen and oxygen, as well as the water when the fuel cell stacks are generating power. Terrestrial operations do not need to store oxygen in order to operate, since air can be fed through the cathode on a one-pass basis, thereby eliminating the need for high pressure storage of a highly oxidizing reactant. Of course the water generated must still be captured from the cathode exhaust for subsequent feed to the electrolyzer. Another simplification is the precision within which the duty cycle for hydrogen and oxygen production is prescribed. On the Lunar surface there is no interference in the solar spectral interaction schedule on the PV, except for a Lunar eclipse. One Lunar day cycle is actually 29 Earth days, 12 Earth hours, 24 Earth minutes and 2.9 Earth seconds, and the periods and intensity of light and dark are nearly constant, making the control and planned storage and utilization of reactants very easy to schedule and maintain. When operating an electrolyzer at high pressure, pumping water to high-operating pressure is much more efficient than compressing hydrogen to the point where the cross-over inefficiencies for PEM electrolyzers offset it, - at 70% efficiency at 15 M Pa has been reported. Terrestrial operations, however, are not as easy to accommodate because of the variations in latitude, cloud cover potential, and other phenomenon which can cause shading or blockage of the solar spectrum, physical damage and weathering on the PV array surfaces, and/or widely varying thermal cycling. This creates a major difference in the control considerations that need to be investigated in the JPL testbed operations. For example, high pressure operation during cloudy periods **when intermittent interruptions of solar radiation on the PV may occur** could cause a safety shutdown. Delays in startup and recovery to high pressure and high current density conditions could jeopardize the successful production of hydrogen for some terrestrial operations. Unless the unit can be grid-connected, or interconnected with backup electrical power or a separate hydrogen source, the concern for maintaining adequate quantities of hydrogen or hydrogen production for continuous, uninterrupted power is in question. Therefore, alternate methods of operation for completely stand-alone terrestrial operation must be provided that are not necessary for Lunar activities.

System trades are necessary to determine the most efficient operations for terrestrial use. From the information that will be generated from the JPL testbed, the technical and economic issues associated with controls strategy and efficiency of operations will be addressed and evaluated for commercial, as well as for NASA, benefit.

SUMMARY

The NASA LeRC solar RFC testbed is a unique facility. Inherent with its design, equipment and operational capabilities, it offers the capability for conducting a multitude of component, subsystem and integrated system evaluations. In its present configuration, this facility includes: (1) a 25 kW PEM electrolysis unit which operates off either a grid connection or solar array, can produce hydrogen (at rates up to 2.36 sls) and oxygen (at rates up to 1.18 sls) at pressures up to

20.7 MPa under either manual or computer control; (2) capacity to store dried hydrogen **(up to 0.46 m^3) at pressures to** 20.7 MPa and dried oxygen (up to 0.36 m^3) at **pressures to 17.2** MPa; (3) operate fuel cells at either of two test locations under pressures from 2.9 to 14.5 kPa, with varying oxygen concentrations, currently with PEM and 50% recirculation through 20 kW stacks, at temperatures to 363 k and electrical loads to 35 kW under either manual or computer control; 4) deliver 50 kW of DC electricity from two separate 500 VDC 25 kW PV arrays, and 6) integrate automation of temperature/pressure/flow controls through two separate computer stations with integrated data collection and storage/retrieval/reduction capabilities. Furthermore, the integration of these subsystems for evaluation of system optimization is underway with specific hardware operations.

Parametric analyses of solar RFC systems, based upon data derived from the testbed operations, will be conducted by JPL as more operating information is accumulated. Based upon a computer model developed from previous fuel cell systems analyses, the efficiencies of the fuel cell stacks and electrolyzer, determined from various operating flow rates, pressures, and loads will be used to define component specifications and subsystems operating ranges to optimize performance and footprint. Application requirements will also be incorporated **in test and performance conditions that will be** used in future operations.

ACKNOWLEDGEMENTS

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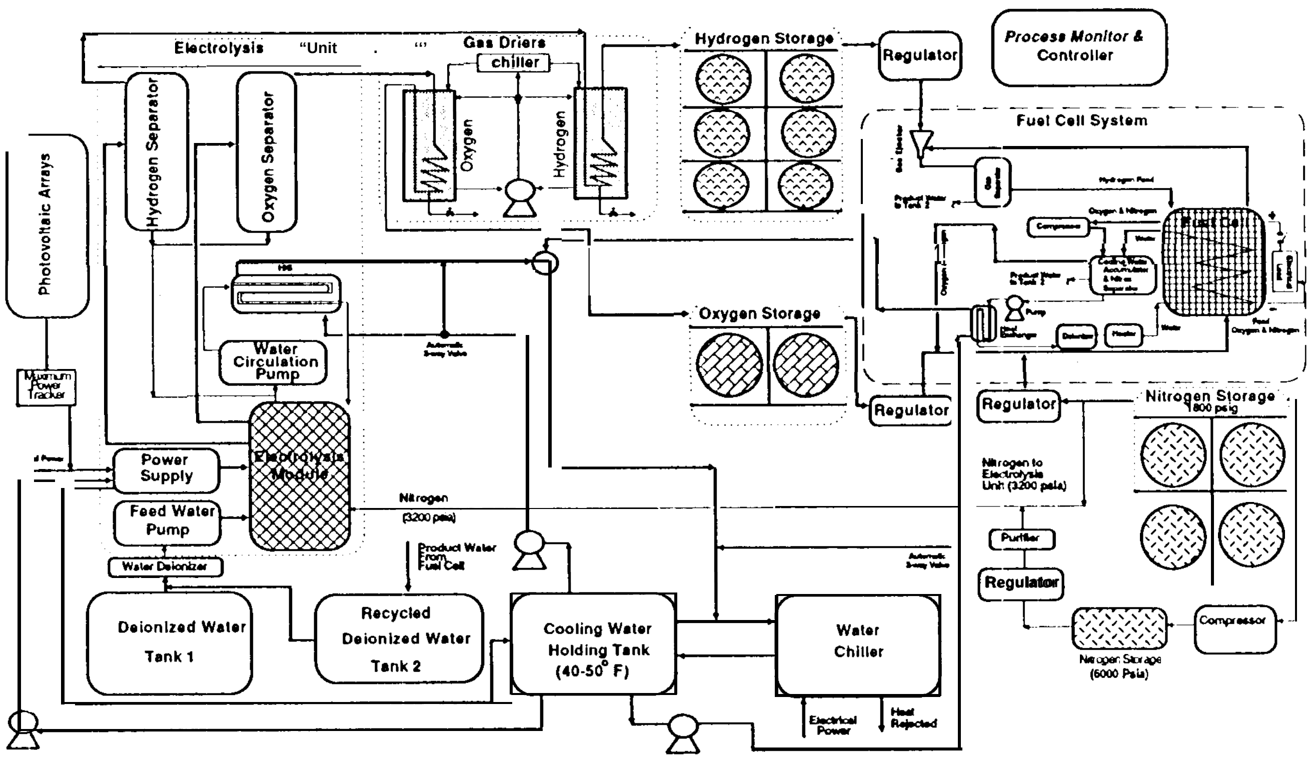

FIGURE 1 SCHEMATIC OF THE SOLAR REGENERATIVE FUEL CELL TESTBED SUBSYSTEM INTEGRATION

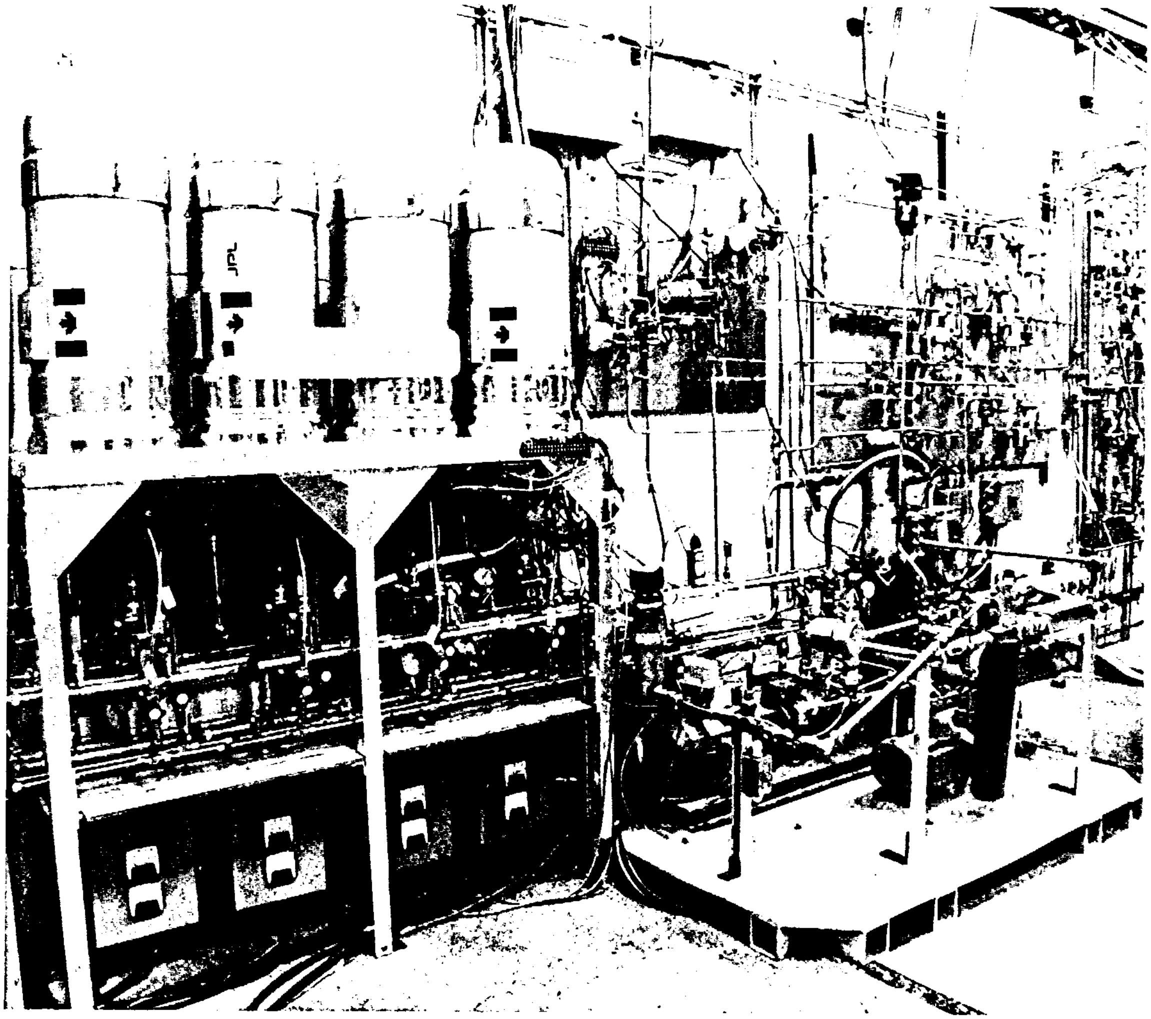

FIGURE 2 VIEW OF THE FOUR 5 KW PEM FUEL CELL STACKS AS INTEGRATED WITH THE DELIVERY SYSTEM

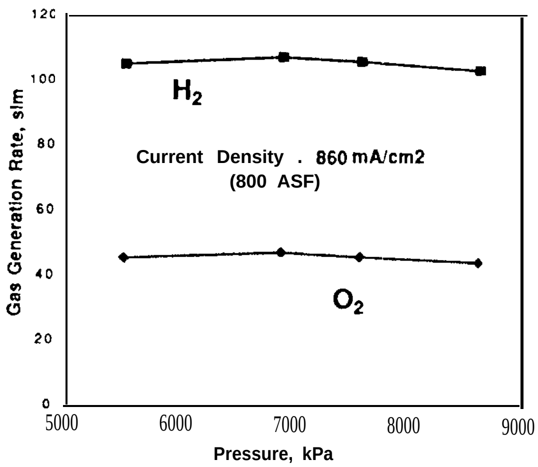

FIGURE 3 EFFECT OF PRESSURE ON GAS GENERATION RATE AT CONSTANT CURRENT DENSITY

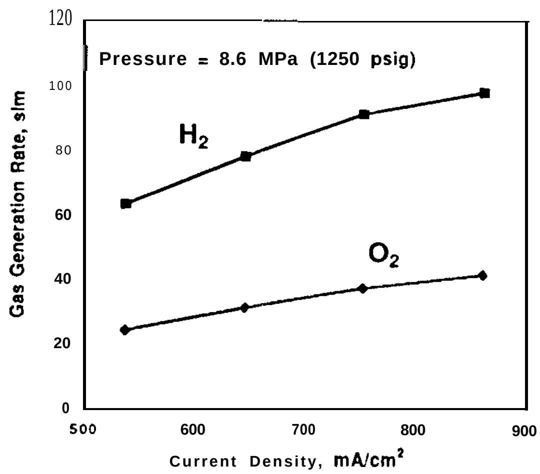

FIGURE 4 EFFECT OF CURRENT DENSITY ON GAS GENERATION RATE AT CONSTANT PRESS.

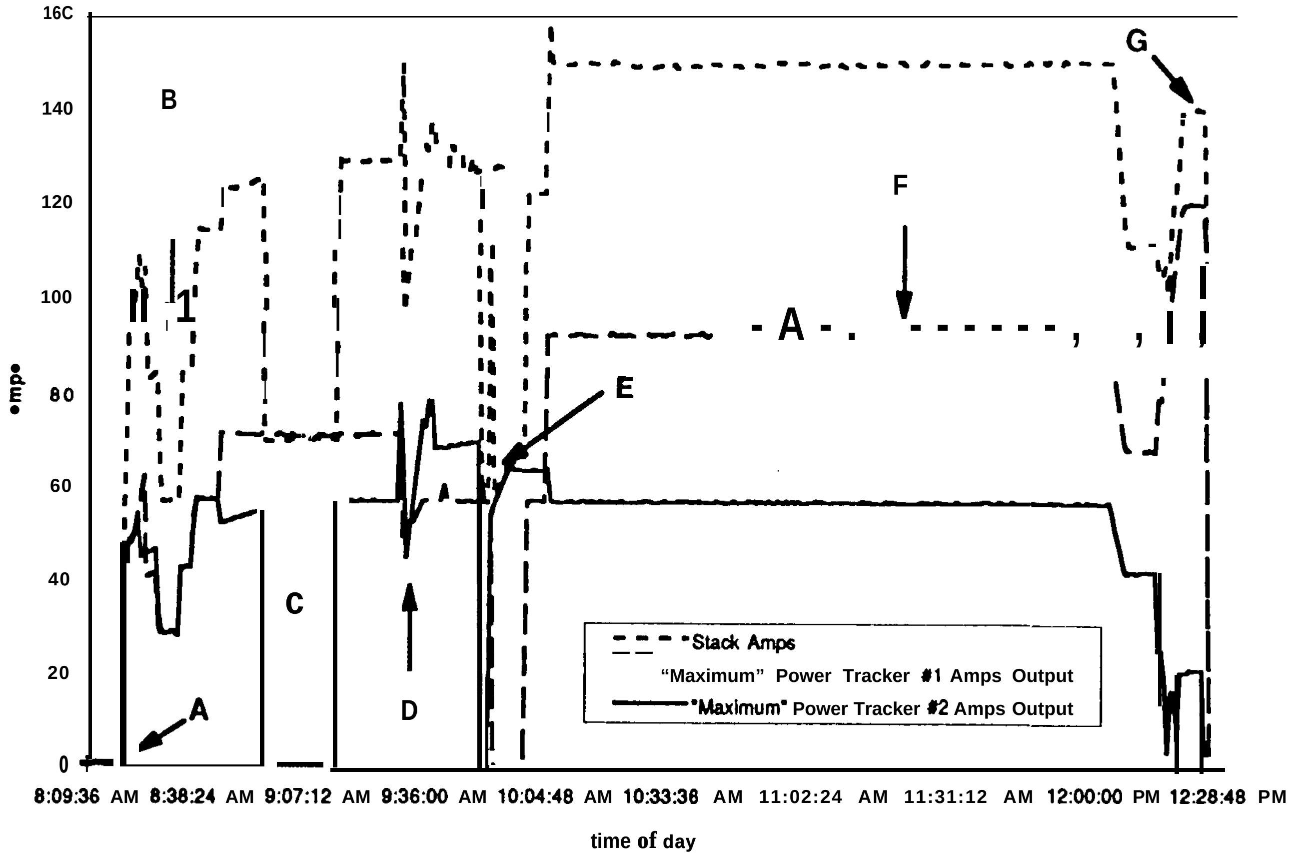

FIGURE 5 ILLUSTRATION OF REMOTE CONTROL CAPABILITY ON SOLAR ARRAY POWER SUPPLY TO ELECTROLYZER

A. AUTOMATIC STARTUP ON SOLAR POWER
B. PARALLEL EQUIVALENT CHANGES ON AMPERAGE LEVEL FROM ARRAYS AT CONSTANT LOAD
C. INDEPENDENT OPERATION OF ELECTROLYZER ON A SINGLE ARRAY
D. REMOTE SWITCHING OF LOAD LEVELS AND RATIOS BETWEEN ARRAYS UNDER LOAD
E. REMOTE SWITCHING OF TOTAL LOAD TO ONE ARRAY
F. CONSTANT PERFORMANCE AT 65/35 SPLIT IN LEVEL OF AMPERAGE DELIVERY
G. REMOTE MANUAL SHUT DOWN UNDER LOAD